

ON THE FORMATION OF MULTIPLE STELLAR POPULATIONS IN GLOBULAR CLUSTERS

CHARLIE CONROY & DAVID N. SPERGEL

Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA

Submitted to the Astrophysical Journal

ABSTRACT

Nearly all globular clusters (GCs) studied to date show evidence for multiple stellar populations, in stark contrast to the conventional view that GCs are a mono-metallic, coeval population of stars. This generic feature must therefore emerge naturally within massive star cluster formation. Building on earlier work, we propose a simple physical model for the early evolution (several 10^8 yr) of GCs. We consider the effects of stellar mass-loss, type II and prompt type Ia supernovae, ram pressure, and accretion from the ambient interstellar medium (ISM) on the development of a young GC's own gas reservoir. In our model, type II SNe from a first generation of star formation clears the GC of its initial gas reservoir. Over the next several 10^8 yr, mass lost from AGB stars and matter accreted from the ambient ISM collect at the center of the GC. This material must remain quite cool ($T \sim 10^2$ K), but does not catastrophically cool on a crossing time because of the high Lyman-Werner flux density in young GCs. The collection of gas within the GC must compete with ram pressure from the ambient ISM. After several 10^8 yr, the Lyman-Werner photon flux density drops by more than three orders of magnitude, allowing molecular hydrogen and then stars to form. After this second generation of star formation, type II SNe from the second generation and then prompt type Ia SNe associated with the first generation maintain a gas-free GC, thereby ending the cycle of star formation events. Our model makes clear predictions for the presence or absence of multiple stellar populations within GCs as a function of GC mass and formation environment. While providing a natural explanation for the approximately equal number of first and second generation stars in GCs, substantial accretion from the ambient ISM may produce fewer chemically peculiar second generation stars than are observed. Analyzing intermediate-age LMC clusters, we find for the first time evidence for a mass threshold of $\sim 10^4 M_\odot$ below which LMC clusters appear to be truly coeval. This threshold mass is consistent with our predictions for the mass at which ram pressure is capable of clearing gas from clusters in the LMC at the present epoch. Recently, claims have been made that multiple populations within GCs require that GCs form at the center of their own dark matter halos. We argue that such a scenario is implausible. Observations of the young and intermediate-age clusters in the LMC and M31 will provide strong constraints on our proposed scenario.

Subject headings: Galaxy: globular clusters — globular clusters: general — stars: evolution

1. AN OBSERVATIONAL PUZZLE

Globular clusters (GCs) have historically been considered coeval, mono-metallic, gravitationally bound collections of stars. In the past several years, high precision photometric and spectroscopic observations have led to a radical revision of this picture.

High resolution spectra of stars within nearly all GCs studied to date reveal internal spreads in light element abundances such as C, N, Na, O, Mg, and Al, beyond what can be explained by measurement errors (see review in Gratton et al. 2004). The magnitude of the internal spread varies considerably from cluster to cluster, though there are noticeable trends with cluster mass and orbital properties (Carretta 2006; Carretta et al. 2010c). Intriguingly, internal spread in the Fe-peak elements and the type II supernovae product Ca is limited to only the most massive GCs (ω Cen, M22, M54, and Terzan 5; Marino et al. 2009; Carretta et al. 2009a; Ferraro et al. 2009; Carretta et al. 2010a,c). The most massive clusters also show indirect evidence for a large spread in He abundances (Gratton et al. 2010). Abundance variations have been detected in main sequence stars (Gratton et al. 2001), indicating that the observed variation arises from stars forming out of different material, as opposed to being due to some unknown mixing process, which could only occur along the giant branch. While much attention has been paid to internal abundance spreads recently, such internal spreads have been

known for over 30 years (Cohen 1978; Kraft 1979; Peterson 1980; Freeman & Norris 1981; Smith & Norris 1982b, 1983).

Photometry from the *Hubble Space Telescope* (HST) has demonstrated that many GCs contain multiple sub-giant branches and at least two (ω Cen and NGC 2808) contain multiple main sequences (see review in Piotto 2009). Variations in the light element abundances have been conclusively associated with the multiple sequences observed in the color-magnitude diagram (CMD; Yong et al. 2008; Marino et al. 2008; Carretta et al. 2009b; Milone et al. 2010), demonstrating that these two phenomena are intimately linked. The population with enhanced abundance patterns is more centrally concentrated than the ‘normal’ population in the GCs NGC 1851 (Zoccali et al. 2009) and ω Cen (Sollima et al. 2007), and perhaps many others as well (Carretta et al. 2009b).

In the old Milky Way (MW) GCs the relative numbers of stars with ‘anomalous’ and normal abundances ratios is approximately equal, with little dependence on metallicity (e.g., Smith & Norris 1982b; Carretta et al. 2009b). This fact imposes strong constraints on formation scenarios, as we explain in later sections. The relative numbers of anomalous and normal stars in GCs in other galaxies (e.g., the LMC, M31) is not known, but would provide new insight.

Additional insight has come from the strong observed correlations between various light element abundances within individual GCs. The most striking is the anti-correlation be-

tween Na and O (e.g., Kraft et al. 1993; Ivans et al. 1999; Carretta et al. 2009b). This correlation arises naturally when material of standard (e.g., solar) abundance ratios is mixed with material that has been processed¹ at temperatures $> 10^7\text{K}$. At such temperatures the Na-Ne and CNO cycles are active, with the former producing Na and the latter depleting O. At similar temperatures the Mg-Al cycle is active, explaining observed correlations between these elements as well.

The discovery of significant Li and F abundances in the second stellar generation (i.e., associated with stars of high Na and low O abundances; Pasquini et al. 2005; Smith et al. 2005) has provided yet another puzzle and clue. These elements are fragile, especially Li which burns at $T \gtrsim 10^6\text{K}$. The existence of such fragile elements in the atmospheres of second generation stars that also show strong O depletion and Na enhancement suggests that these stars formed out of at least two kinds of material; i.e., from matter exposed to $T > 10^7\text{K}$, and additional material that was never heated above $T \sim 10^6\text{K}$. The interpretation of Li is however complicated by the possibility that Li may, under special circumstances, actually be produced within AGB stars (see e.g., Ventura & D’Antona 2010).

Multiple stellar populations have also been detected in intermediate-age ($\sim 1\text{ Gyr}$) and old LMC clusters (Mackey et al. 2008; Goudfrooij et al. 2009; Milone et al. 2009; Mucciarelli et al. 2009), and possibly in the old GCs within the Fornax dSph galaxy (Letarte et al. 2006). These observations indicate that the multiple stellar population phenomenon is not specific to the MW. Observations of LMC clusters are of course hampered by the much larger distance modulus to the LMC. Despite this limitation, the intermediate-age clusters offer a new window into the internal age spreads because the main sequence turn-off point at these ages is a strong function of time. Small age differences are therefore readily noticeable in the CMD. Analysis of *HST*-based CMDs have shown that the spread observed in the main sequence turn-off of intermediate-age LMC clusters can be explained with an internal age spread of a few 10^8 yr .

The only class of star clusters known *not* to contain multiple stellar populations are the open clusters in the MW (de Silva et al. 2009; Martell & Smith 2009), which have typical masses of a few thousand solar masses, although some, such as NGC 7789, have masses of $\sim 10^4 M_\odot$.

These observations have led to the unavoidable conclusion that the majority of GCs studied to date harbor multiple stellar populations. For all but the most massive ones, GCs are still considered chemically homogeneous in Fe-peak and elements arising primarily from SNe type II such as Ca. The light element variations have been detected in both young and old clusters, both metal-poor and metal-rich (Martell & Smith 2009), and are noticeably absent in the open clusters.

From these observations the following timeline in the early evolution of GCs has emerged. Within GCs, a first generation of stars form. Type II SNe then remove any remaining gas from the GC. After the epoch of type II SNe, mass from evolved stars is cycled through temperatures of $T > 10^7\text{K}$ and then is returned to the gaseous reservoir of the GC. After a few 10^8 yr , a second generation of stars forms from a mix of processed and un-processed material. Star formation

permanently ceases after the formation of the second generation. This process does not occur in open clusters, nor in the field. This basic timeline has, in one form or another, been discussed by many authors (e.g., Cottrell & Da Costa 1981; Smith 1987; Carretta et al. 2010b).

Any theory of GC formation must be embedded into our broader cosmological theories of structure formation. Many lines of evidence suggest that galaxy formation is an hierarchical process where dark matter halos serve as sites for assembling baryons and converting baryons into stars. One of the inevitable predictions of this bottom-up scenario is that MW GCs likely formed in environments very different from the $\sim 200\text{ km s}^{-1}$ dark matter dominated halo where they now reside. One possibility, which we discuss in §2.1.1, is that GCs form in the centers of small dark matter halos. This scenario would imply that isolated GC are embedded in extended dark matter halos. This paper emphasizes another possibility: GCs form within small gas-rich dwarf galaxies — the building blocks of the present MW. We emphasize that the MW is an evolving galactic system so that estimates of ram pressure and gaseous accretion must consider the likely environment in which a GC formed at $z \sim 2 - 10$, rather than its current location in the MW today.

We have outlined above only the most basic sketch of what must occur to explain the observations. In the next section we critically assess previous, more detailed scenarios for the development of multiple stellar populations within GCs. Following this assessment, we describe our own model for the early evolution of GC stellar populations that includes several novel ingredients, and is, at least in certain respects, more plausible than other scenarios. We also present an analysis of intermediate-age clusters in the LMC that provides confirmation of a key aspect of our model. We conclude by commenting on various observations that may shed new light on this exciting observational puzzle.

2. PREVIOUS EFFORTS

There are at least three major issues that require explanation before any satisfactory theory for the formation of multiple populations in GCs can be accepted. These are: 1) understanding how the gaseous reservoir within a GC can remain within the shallow potential well for several 10^8 yr ; 2) identifying which stars are responsible for processing material at $T > 10^7\text{K}$; and 3) explaining how a second generation of stars can form with a current total mass comparable to the first generation. In this section we will assess the plausibility of previous efforts at addressing these outstanding issues.

2.1. Can mass lost from first generation stars remain bound to the GC?

A serious challenge to any theory for the formation of multiple stellar populations is the shallow potential wells of GCs. If gas is to remain bound within GCs, then one of the following two scenarios must occur: 1) the gas must both be ejected from stars below the GC escape speed and must remain cool so that the internal dispersion is $\lesssim 10\text{ km s}^{-1}$; or 2) the GC must be at the gravitational center of a more massive system with the escape speed from the larger system sufficiently large to retain stellar winds of a range of speeds.

An additional obstacle is ram pressure. Many GCs cross the disk of the MW at high velocity, which results in a strong ram pressure force felt by gas within GCs. Under certain conditions, ram pressure may therefore prohibit the formation of a

¹ Throughout the text we will use ‘processed’ and ‘un-processed’ to refer specifically to the nuclear processing of material at the temperatures required to explain the observed light element abundance variations, i.e., at $T > 10^7\text{K}$.

gaseous reservoir within GCs (see e.g., Frank & Gisler 1976; Gnedin et al. 2002).

The shallow potential wells of GCs and their susceptibility to ram pressure has led some to resurrect the notion that GCs form at the center of their own dark matter halos at high redshift (e.g., Bekki & Norris 2006; Bekki et al. 2007; Carretta et al. 2010b). The feasibility of this scenario is assessed in the following section.

2.1.1. Formation of GCs at the centers of small dark matter halos?

Early theories regarding the formation of GCs included the possibility that they form within extended dark matter halos at high redshift (Peebles 1984). This scenario fell out of favor following the observation of thin tidal tails surrounding many GCs (e.g., Grillmair et al. 1995; Odenkirchen et al. 2003), because numerical simulations showed that such tidal tails do not form if GCs reside within extended halos (Moore 1996).

The formation of GCs at the center of their own dark matter halos has received renewed interest thanks to numerical work that has shown that extended halos of GCs could be tidally stripped away by the present epoch (Bromm & Clarke 2002; Mashchenko & Sills 2005). In this picture, the constraint from tidal features demonstrates only that GCs at the present epoch are not embedded within extended massive halos, but offers no insight into the formation environment of GCs.

This scenario has been adopted in order to explain the formation of multiple stellar populations within GCs (e.g., Freeman 1993; Bekki & Norris 2006; Bekki et al. 2007; Böker 2008; Carretta et al. 2010b) for the principle reason that GCs embedded within massive halos do not experience ram pressure and may also easily retain stellar winds. In our opinion, the motivation for dark matter halos from ram pressure arguments is in error. Recent arguments regarding ram pressure have been based directly on ram pressure calculations for GCs orbiting the MW *at the present epoch*. Indeed, no GCs today show evidence of a gaseous reservoir, and ram pressure is thought to be responsible (see e.g., Tayler & Wood 1975; Frank & Gisler 1976). These calculations assume mass-loss rates appropriate for $\sim 10^{10}$ yr old populations, and orbital velocities characteristic of the present MW. In contrast, at the epoch relevant for the formation of multiple populations (e.g., the formation epoch of GCs), the characteristic orbital velocities were almost certainly substantially smaller, probably by an order of magnitude, and the mass-loss rates were an order of magnitude larger. We will demonstrate quantitatively in a later section that these two effects combine to significantly reduce the efficiency of ram pressure so that all MW and LMC clusters that show evidence for multiple stellar populations were likely impervious to this effect in their formation environment, without appeal to dark matter halos. In short, ram pressure is *not* an important physical process for the mass ranges and formation environments of the current set of clusters with known multiple populations.

There are additional arguments against the formation of GCs within dark matter halos. The most striking is the observation of multiple populations within intermediate-age LMC clusters. These clusters surely are not embedded within massive halos, and yet they clearly are capable of forming multiple populations. If these clusters can form multiple populations without being embedded in a massive halo, why not MW GCs?

If GCs formed at the center of their own halos, then the existence of GCs within dwarf spheroidals would be extremely

difficult to understand because they would have very short dynamical friction times. For example, Fornax contains five GCs. In the absence of an extended massive halo, the friction timescales are already uncomfortably short if Fornax resides within a standard dark matter halo (several Gyr; Goerdt et al. 2006). If these GCs were embedded in massive halos, their dynamical friction timescales would be $\ll 1$ Gyr since friction scales with the total GC mass.

A final argument against GC formation within extended halos is the structure and kinematics of very isolated GCs both in the MW and M31. NGC 2419 is a remote MW GC at a distance of ≈ 90 kpc from the Galactic center, has a mass of $\sim 10^6 M_\odot$, and half-mass radius of ≈ 20 pc. Based on radial velocity measurements of stars within NGC 2419, Baumgardt et al. (2009) measured a mass-to-light ratio that was consistent with a pure stellar population. It is hard to imagine how tidal stripping could effect this cluster, and so the lack of any evidence for a massive dark matter halo for NGC 2419 argues against GCs generically forming within massive halos. Recently, an extremely isolated GC has been found within M31, at a distance of ≈ 200 kpc from the center of M31 (Mackey et al. 2010). This object, far removed from any strong tidal fields, should be another ideal candidate to search for evidence of dark matter within GCs.

The formation of GCs within massive halos does however provide one significant advantage over models that do not invoke formation within halos. At high redshift (e.g., $z = 10$), the gas accretion rate onto a 10 km s^{-1} halo from the intergalactic medium is of the order $\rho_{\text{IGM}} V 4\pi R^2 \approx 6 \times 10^{-3} M_\odot \text{ yr}^{-1}$. The accretion rates are much higher at $z = 10$ than the present epoch because the density of the IGM is higher by a factor of $(1+z)^3 = 10^3$. After several 10^8 yr, this would result in a substantial accumulation of gas, which could help explain the relative numbers of first and second generation stars (see §2.3) and the high abundances of Li and F.

In this section we have argued that 1) GCs need not form at the centers of their own halos in order to survive ram pressure stripping and 2) regardless of ram pressure considerations, not all GCs could have formed within their own halos given both dynamical constraints and observations of intermediate-age GCs in the LMC and M31. Nonetheless, we emphasize the possibility that *some* GCs formed at the centers of their own halos. Nuclear star clusters reside at the centers of galaxies, are massive ($\sim 10^6 - 10^8 M_\odot$), compact (half-light radii of a few pc), and span a wide range of ages ($10^7 - 10^{10}$ yr; Böker et al. 2004; Walcher et al. 2005, 2006). The youngest nuclear star clusters must certainly have formed where they are now observed. The formation environment of the older clusters is less clear because they may have migrated toward the center via dynamical friction. In any event, the existence of nuclear star clusters at least suggests that GC-like objects can in some cases form at the centers of their own dark matter halos. As we discuss below, the most massive GCs in the MW may be examples of such objects.

2.2. Identifying the stellar type responsible for processing material to $T > 10^7 \text{ K}$

Based on nucleosynthetic constraints, there are two plausible candidate donors of processed material: massive ($\gtrsim 20 M_\odot$) rotating stars (Decressin et al. 2007), and massive ($\approx 4 - 8 M_\odot$) AGB stars (Ventura et al. 2001; D’Antona et al. 2002). Unfortunately, both of these proposed sites suffer from serious theoretical uncertainties (e.g., compare the AGB mod-

els of Karakas & Lattanzio (2007) and Ventura & D’Antona (2008b)). The relevant cross-sections for the production of Na are uncertain by a factor of ~ 1000 (see discussion in Ventura & D’Antona 2008b), making detailed comparisons between models and data difficult. For example, Ventura & D’Antona (2008a) were able to construct AGB models whose ejecta abundance patterns were consistent with the abundances of observed second generation stars only after they modified several key yet uncertain nuclear cross sections. Models for massive rotating stars suffer from significant uncertainties not only in the mass loss rates but also in the efficiency of meridional circulations to mix processed material to the envelope.

The massive rotating stars model suffers from several shortcomings. First, the timescale for these stars to lose mass is comparable to the timescale for type II SNe. It is difficult to imagine how new stars could form in an environment where massive stars are constantly exploding. Even if this could occur, the second generation would then show significant over abundances in α -elements compared to the first generation, but this is not observed (see also Renzini 2008, who make a similar point).

Moreover, the short timescales involved would imply that a different physical mechanism is at work in the intermediate-age LMC clusters, where CMD studies have shown internal age spreads of order 10^8 yr (Milone et al. 2009). In contrast, the AGB stars evolve on timescales similar to the observed age spread in LMC clusters, providing a natural explanation for the observed spread.

Finally, the short evolutionary timescales for the massive rotating stars makes it difficult to explain the observed Li and F abundances. The most plausible explanation for the relatively high abundances of these elements is that the second generation formed from a mix of un-processed and processed material. As we discuss in later sections, it is very difficult to accrete a sufficient amount of un-processed material in only $\sim 10^7$ yr.

Recently, de Mink et al. (2009) proposed a scenario whereby massive binaries shed a large fraction of their mass due to non-conservative mass and angular momentum transfer. We believe that this scenario suffers from many of the shortcomings of the winds from massive stars scenario, as outlined above, and is therefore also disfavored.

We instead favor AGB stars as the source of processed material out of which the second generation stars form. Besides the fact that they are the only remaining option, the evolutionary timescale of massive AGB stars is comparable to the inferred internal age spread within intermediate age GCs in the LMC.

2.3. Constraints imposed by the relative numbers of first and second generation stars

As emphasized by many authors, it is very difficult to understand the observational fact that within most GCs the number of first and second generation stars is approximately equal. For example, assuming a standard Kroupa (2001) IMF, and assuming that AGB stars shed all of their mass aside from a $0.6M_{\odot}$ white dwarf remnant mass, only $\approx 9\%$ of the total initial stellar mass of the system can be returned to the surrounding GC from AGB winds with initial masses of $4-8M_{\odot}$.² If 100% of the AGB ejecta were converted into stars, the popu-

lation ratio should be approximately ten first generation stars for every one second generation star.

Several scenarios have been proposed to account for the discrepancy between the above expectation and the observed ratio. Early proposals focused on ad hoc variations to the IMF in order to produce the observed relative numbers (e.g., Smith & Norris 1982a). Recent work has even attempted to *constrain* the IMF of the first generation in this way (D’Antona & Caloi 2004; Prantzos & Charbonnel 2006).

More recently, D’Ercole et al. (2008) proposed a solution that required the first generation to have been substantially more massive (by a factor of $10-100$) than its present mass. If the first generation was born with mass segregation already in place, then stellar evolutionary and dynamical effects could result in the loss (i.e., unbinding) of a significant number of first generation stars. The second generation, being born with higher concentration, would be relatively immune to such a process, and so the majority of second generation stars would remain bound. The preferential loss of first generation stars could then result in comparable numbers of first and second generation stars at late times.

The proposal that second generation stars form purely from AGB ejecta suffers from several shortcomings, including the required level of fine-tuning. If we assume that the first generation donates 10% of its mass to the GC gas reservoir via AGB winds and a star formation efficiency of 30%, the resulting total mass in the first and second generations will be equal if the first generation loses 97% of its initial mass. This assumes that no stars from the second generation are lost; any mass lost from the second generation would require an even larger fraction of mass-loss from the first generation. In the D’Ercole et al. (2008) scenario, the first generation of every GC must lose $\gtrsim 97\%$ of its mass so that the observed population ratios are always of order unity. Without a natural mechanism to explain why the first generation always sheds enough mass so that its final mass is comparable to the second generation, the mass lost must be fine tuned *ad hoc*. One would also expect isolated GCs such as NGC 2419 that experience weak tidal fields to contain many more (by factors of $10-100$) first generation compared to second generation stars. Abundance measurements of stars within NGC 2419 currently do not exist but would clearly shed light on this issue.

A second concern with the D’Ercole et al. solution is the large remnant population left behind by the disproportionately large fraction of massive first generation stars at the center of the GC. In this scenario, a GC with present mass $10^5 M_{\odot}$ and equal numbers of first and second generation stars would require an initial stellar mass of $\sim 10^7 M_{\odot}$ first generation stars in order to generate enough gas from AGB winds to produce a second generation with total mass $\sim 10^5 M_{\odot}$. For a standard Kroupa (2001) IMF, approximately 10% of the total initial mass is constituted by $M > 8M_{\odot}$ stars. If 10% of these massive first generation stars are concentrated toward the center because of mass segregation and then explode, a population of neutron stars and black holes will be left behind, and remain bound, with a total mass of $\sim 10^4 M_{\odot}$!

$1M_{\odot}$ can contribute to the GC’s gaseous reservoir. The main sequence lifetime of such stars is substantially longer than $\sim 10^8$ yr, and in addition it is believed that hot bottom burning, which is the source of many of the abundance anomalies, does not occur in such low mass stars. We therefore believe our fraction, which is based on the expected AGB mass range for hot bottom burning, to be more accurate. Expanding the adopted mass range to $3-8M_{\odot}$ results in a mass return fraction only slightly larger (13%) than what we quote for the $4-8M_{\odot}$ range.

² Our returned mass fraction is substantially smaller than the fractions quoted in Bekki & Norris (2006) because they assume AGB stars down to

Such a large population of massive remnants would not only be detectable as an additional dark mass component concentrated toward the dynamical center, but would also imply a very high incidence of low-mass X-ray binaries (LMXB). Neither of these predictions are supported by the observations (e.g., van der Marel 2004; Verbunt & Hut 1987), although there are notable caveats. The observed frequency of LMXBs can be naturally explained by the high rate of binary formation in GCs compared to the field, although this mechanism is quite uncertain (Fabian et al. 1975; Verbunt & Hut 1987). We have assumed that a significant fraction of neutron stars remain bound to the cluster, which may not be true if the majority of GC neutron stars are born with high kick velocities (as appears to be the case for pulsars in the MW; Hansen & Phinney 1997). Appealing to IMF variations to explain the relative numbers of first and second generation stars would also produce significantly more neutron stars and black holes, as pointed out by D’Antona & Caloi (2004). A more careful analysis of the expected remnant population in GCs may yield stronger constraints on these models.

Recently, Sills & Glebbeek (2010) have investigated the importance of stellar collisions in boosting the number of fast rotating massive stars and intermediate mass stars (i.e., AGB stars) in GCs. These authors find that stellar collisions are not sufficiently numerous for their products to help explain the relative number of first and second generation stars.

In the following section we propose an alternative scenario for resolving this discrepancy that is based on adding a significant amount of gas via accretion from the ambient ISM.

3. A PLAUSIBLE MODEL FOR THE FORMATION OF MULTIPLE STELLAR POPULATIONS IN GLOBULAR CLUSTERS

In the previous section we evaluated a number of current scenarios that address aspects of the formation of multiple stellar populations within GCs. In this section we propose an alternative scenario for the formation of multiple stellar populations in GCs.

3.1. Model overview

Our scenario can be summarized as follows. A first generation of stars forms out of gas that has already been pre-enriched to GC abundances. Type II SNe expel the remaining gas and thus shut off star formation. Over several 10^8 yr, mass lost from massive AGB stars is returned to the gaseous reservoir of the GC. In addition, *over this same time period, mass is accreted onto the GC from the ambient ISM.* This un-processed gas is *incompletely* mixed with the AGB ejecta. All of the gas within the GC must be relatively cold ($T \sim 10^2$ K), which implies efficient cooling. However, this gas does not cool catastrophically for several 10^8 yr because of the high Lyman-Werner photon density, which photodissociates molecular hydrogen (H_2). After several 10^8 yr, the Lyman-Werner photon density drops by more than three orders of magnitude (see Figure 1), H_2 rapidly forms, and star formation is triggered within the GC’s gas reservoir. A second generation of stars is born. Type II SNe from the second generation clear out the remaining gas³. On a similar timescale as the formation of the second generation (several

10^8 yr), prompt type Ia SNe from the first generation begin to explode. These SNe then act to maintain a gas-free GC environment, thereby permanently ending star formation.

Notice that GCs do *not* form in the centers of dark matter halos in our scenario. Rather, in our scenario, GCs form wherever ISM conditions are favorable, including within gas-rich dwarf galaxies and interacting systems; the former being the presumed building blocks of the present day MW. Evidence for efficient GC formation within gas-rich dwarfs can be found in the high specific frequencies of GCs within dwarfs compared to L^* galaxies (Lotz et al. 2004).

This model contains several novel ingredients with respect to previous work. First, we invoke significant accretion from the ambient ISM during the development of the GC gas supply (see also Pflamm-Altenburg & Kroupa 2009; D’Ercole et al. 2010). Second, we appeal to the importance of the high Lyman-Werner photon flux density in delaying star formation for several 10^8 yr. Third, we assert (and quantify below) that GC formation in the centers of dark matter halos is not a necessary condition for the formation of multiple stellar populations because ram pressure is not effective at stripping the GC’s gas reservoir at early times.

We emphasize that certain aspects of this model, described in detail below, are not able to naturally explain the properties of the most massive MW GCs (e.g., ω Cen, NGC 2808, M22, and M54), which show evidence for multiple *distinct* stellar populations, and appear to require very high He abundances ($Y \sim 0.4$). We consider these objects separately in §5.

We now provide observational and theoretical motivations for each of these elements.

- As summarized in §1, there is no internal spread in either the Fe-peak elements or the α -elements (that are unambiguously associated with Type II SNe, e.g., Ca), except for the most massive GCs. This implies that the second generation formed out of material that was *not* enriched by the type II SNe associated with the first generation, nor by Type Ia. We conclude from this that type II SNe efficiently evacuated the remaining gas from the GC after the formation of the first generation. Energetic arguments support this conclusion (e.g., Dopita & Smith 1986; Baumgardt et al. 2008). Notice that any ambient ISM that is later accreted onto the GC must also be unpolluted by these type II SNe. It might be difficult to avoid this if GCs form at the center of their own dark matter halos.
- Consideration of the effects of type II SNe leads us to disfavor winds from massive rotating stars as the source of the processed material (i.e., the scenario proposed by Decressin et al. 2007). These stars evolve on timescales comparable to the onset of type II SNe. It is therefore very difficult to see how a second generation of stars could form out of the mass lost via winds from these massive stars both because the SNe would tend to expel the gas, and also because if the gas remained, it would be enriched in α -elements, which is not observed (see also §2.2 and Renzini 2008). We therefore favor AGB ejecta as the source of the processed material.
- Evidence for accretion of pristine material comes from the observed abundance variations and abundance correlations within GCs. Prantzos et al. (2007), Ventura & D’Antona (2008a) and Ventura & D’Antona

³ Of course, star formation must occur on a short enough timescale so that type II SNe do not prohibit the formation of the second generation. Star formation must also occur over a short timescale during the formation of the first generation. This has been a long-standing theoretical problem in the formation of bound GCs.

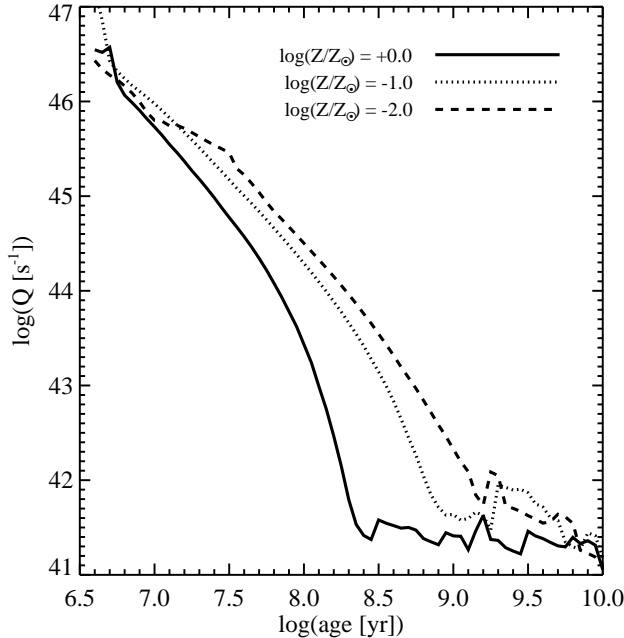


FIG. 1.— Evolution of the Lyman-Werner photon production rate for coeval stellar populations with metallicities of $\log(Z/Z_{\odot}) = 0.0, -1.0$ and -2.0 . Rates are based on the stellar population synthesis models of Conroy et al. (2009) and are normalized such that one solar mass of stars formed instantly at $t = 0.0$. Notice the rapid decline in the rate at several 10^8 yr. Lyman-Werner photons are capable of destroying H_2 and so the precipitous drop in the photon production rate at $t > 10^8$ yr implies favorable conditions for H_2 formation.

(2009) have argued that the Na–O anti-correlation *requires* dilution from pristine material. In addition, Pasquini et al. (2005) and Prantzos et al. (2007) have argued that the discovery of high abundances of Li and F in the second stellar generation requires significant amounts of pristine material. Their argument is based on the fact that these elements are fragile; Li for example burns at $\sim 2 \times 10^6$ K. If the second generation formed purely from AGB ejecta, one might expect these stars to be free of Li and F. Ventura & D’Antona (2010) point out that Li can in fact be made in the convective envelopes of massive AGB stars via the Cameron-Fowler mechanism. The implied yields are however strongly dependent on metallicity, stellar mass, and the adopted mass-loss rates.

The need for dilution from pristine material makes it easier to form a second generation of stars with total mass comparable to the first generation, since second generation stars apparently do not form *exclusively* out of AGB ejecta. Notice that this un-processed material cannot have significantly different Fe-peak nor α -element abundances, which has a number of implications. One implication is that the type II SNe that presumably cleaned out the GC after the first generation was born cannot have mixed with this un-processed material, at least for the MW GCs, for which constraining data are available.

- Stars within GCs with abundance variations display a *range* of Na and O abundances, rather than simply two values as might be expected if the second generation formed from a chemically uniform gas reser-

voir. We interpret this result as evidence of incomplete mixing in the gas between the processed and accreted ambient ISM material. For example, Prantzos et al. (2007) demonstrate that the full range of F and Li abundances can be reproduced in NGC 6742 and M4 with a ‘dilution’ factor of ambient ISM material ranging from 0.1 to 250. Ventura & D’Antona (2008a) and Ventura & D’Antona (2009) have shown that the full range of the Na–O anti-correlation can be explained if stars form from a mixture of AGB ejecta and pristine material. Clearly, the GC gas reservoir must be quite heterogeneous prior to the second generation of star formation.

- Over the past few years, there has been a growing recognition that most type Ia SNe are prompt rather than delayed explosions with timescales of Gyr (Scannapieco & Bildsten 2005). The prompt Ia SNe rate has been estimated to be roughly 10^{-12} SNe $M_{\odot}^{-1} \text{ yr}^{-1}$, which translates into ≈ 10 SNe per $10^5 M_{\odot}$ per 10^8 yr (e.g., Brandt et al. 2010; Maoz et al. 2010), or $\sim 10^{52}$ erg of energy per $10^5 M_{\odot}$ per 10^8 yr. The binding energy of $10^5 M_{\odot}$ of gas with radius 1 pc — an extreme case — is $\approx 10^{51}$ erg. Once they begin to occur (i.e., after the delay time), prompt SNe Ia will therefore be sufficient to keep the GC gas-free. This is an important element. If there were no prompt Ia SNe, it is not clear why a third, fourth, etc. generation of stars would not form from the AGB ejecta of earlier generations. The importance of prompt Ia SNe has also been emphasized by D’Ercole et al. (2008).
- Young GCs produce high flux densities of Lyman-Werner photons ($912 < \lambda < 1100 \text{ \AA}$). These photons are absorbed by H_2 and $\approx 16\%$ will lead to dissociation of the molecule. In Figure 1 we show the flux density of Lyman-Werner photons as a function of time for a coeval stellar population. Notice the precipitous drop in the Lyman-Werner flux density at several 10^8 yr. We are interested in knowing if the flux density at $< 10^8$ yr is sufficiently high to prohibit the formation of H_2 in the bulk of the gas within GCs. This physical situation is analogous to photodissociation regions (PDRs) seen within the MW. In our case we have many, possibly overlapping PDRs because stars are randomly spread throughout the gas within young GCs. The following calculation is an order-of-magnitude estimate that proves to be sufficient for our purposes.

We can compute the radius at which photodissociation of H_2 is equal to the formation of H_2 in a manner analogous to a Strömgren sphere calculation. At the temperatures and metallicities of interest ($T \approx 100\text{K}$, $\log(Z/Z_{\odot}) > -3$), H_2 forms most efficiently on dust grains, with a rate coefficient⁴ of $3 \times 10^{-17} \frac{Z}{Z_{\odot}} \text{ cm}^3 \text{ s}^{-1}$ (Jura 1975; Wolfire et al. 2008). The balance between

⁴ The H_2 formation rate and its dependence on physical parameters is quite uncertain. We adopt a simple linear scaling with metallicity because of the expected linear scaling between metallicity and dust mass fraction. This scaling is supported by Tumlinson et al. (2002) who find that the H_2 formation rate in the LMC and SMC is a factor of ~ 10 lower than in the MW.

formation and destruction occurs at a radius:

$$R_{\text{LW}} = 0.15 \text{ pc} \left(\frac{Q}{10^{46} \text{ s}^{-1}} \right)^{1/3} \left(\frac{10^5 \text{ cm}^{-3}}{n} \right)^{1/3} \left(\frac{0.1 Z_{\odot}}{Z} \right)^{1/3}, \quad (1)$$

where Q is the photon production rate provided by starlight over the interval $912 < \lambda < 1100 \text{ \AA}$, n is the gas density, and Z is the metallicity of the gas. The value of $Q = 10^{46} \text{ s}^{-1}$ is appropriate for a stellar age of $\approx 10^7 \text{ yr}$ (see Figure 1). Notice that we have effectively assigned each GC star an average spectrum appropriate for a coeval population.

This radius is to be compared to the mean interstellar spacing:

$$l = 0.05 \text{ pc} \left(\frac{10^6}{N_*} \right)^{1/3} \left(\frac{R'}{3 \text{ pc}} \right), \quad (2)$$

where N_* is the number of stars within a radius R' . The gas within a young GC will form a considerable amount of H_2 only when $R_{\text{LW}} < l$. Based on the evolution in the flux density shown in Figure 1, this will occur only after several 10^8 yr , when Q decreases by a factor of $> 10^3$. Notice also that even if 90% of the Lyman-Werner photons are absorbed by dust (so that the effective Q is reduced by a factor of 10), the photon flux will still be sufficient to prevent significant formation of H_2 during the early evolution of GCs. The drop in the Lyman-Werner flux density after several 10^8 yr is so dramatic that our conclusion regarding H_2 photodissociation is not sensitive to details.

- The $\sim 10^8 \text{ yr}$ separation between first and second generations is the natural timescale for four completely separate but potentially relevant processes: the orbital time within galactic environments, the main sequence lifetime of massive ($\approx 4 - 8 M_{\odot}$) AGB stars, the timescale for the onset of prompt SNe Ia (e.g., Brandt et al. 2010; Maoz et al. 2010), and the time when Lyman-Werner photon production drops precipitously for a coeval stellar population. The temporal separation between first and second generations cannot be significantly longer than 10^8 yr because otherwise prompt SNe Ia would clear out the GC gas, which would prevent the formation of the second generation. The lack of an internal spread in Fe-peak elements provides additional support to this notion. The orbital timescale may be relevant because tidal perturbations could be a trigger that sets off the second generation of star formation. Once Lyman-Werner photon production drops, H_2 can form, and the gas will catastrophically cool and, presumably, form stars.

In this section we have presented basic arguments favoring our adopted scenario. In the following section we expand upon the topic of the development of a GCs gas supply.

3.2. GC gas reservoir growth and retention

We will now explore the relative importance of ram pressure, Bondi accretion, and the sweeping up of the ambient ISM via simple geometric cross section, as a function of GC mass, M , relative velocity, V , between the ambient ISM and the GC, and density of the ambient medium, n , through with

the GC is moving. In the following discussion we will consider Bondi accretion onto the cluster as a whole, not the accretion of material onto individual stars. Our primary objectives in this section are twofold: to determine to what extent ram pressure prohibits the formation of a second stellar generation, and to determine whether accretion from the ambient ISM can provide a significant source of gaseous material for a second generation of star formation.

An object with mass M embedded within an ambient medium with density n will accrete matter at the Bondi (1952) rate:

$$\dot{m}_B \approx 10^{-5} \left(\frac{M}{10^5 M_{\odot}} \right)^2 \left(\frac{n}{\text{cm}^{-3}} \right) \left(\frac{V}{10 \text{ km s}^{-1}} \right)^{-3} M_{\odot} \text{ yr}^{-1}, \quad (3)$$

where V can be interpreted as the sum in quadrature of the sound speed of the ambient medium and the velocity of the object through the medium. The accretion rate depends somewhat on the equation of state of the ambient medium.

Over 10^8 yr , Bondi accretion will result in a total mass accretion of M_B . After 10^8 yr we therefore have:

$$\left(\frac{M_B}{10^3 M_{\odot}} \right) \approx \left(\frac{M}{10^5 M_{\odot}} \right)^2 \left(\frac{n}{\text{cm}^{-3}} \right) \left(\frac{V}{10 \text{ km s}^{-1}} \right)^{-3}, \quad (4)$$

which, for a given M_B and M results in a simple relation between n and V . In this equation M represents the total mass within the GC. Below, we will approximate M by the “initial” GC mass (i.e., the mass before any gas is accreted). This approximation yields a lower limit to the total mass accumulated via Bondi accretion.

In addition to Bondi accretion, an object moving with velocity V through an ambient medium with density n and cross section A will sweep up material at a rate given by $\dot{m}_S = \rho V A$. The scenario we imagine here is one where a seed gas reservoir is already present within the GC. This seed will then, by collisional forces, be able to sweep up additional gaseous material. This process will occur so long as the ram pressure is less than the restoring force provided by the potential well of the GC (see below). This ambient ISM sweeping results in a mass accretion rate of:

$$\dot{m}_S \approx 1.5 \times 10^{-5} \left(\frac{n}{\text{cm}^{-3}} \right) \left(\frac{V}{10^2 \text{ km s}^{-1}} \right) \left(\frac{R}{3 \text{ pc}} \right)^2 M_{\odot} \text{ yr}^{-1}, \quad (5)$$

where R is the characteristic radius of the gas reservoir within the GC. Notice the relatively strong dependence on radius. After 10^8 yr , a total mass of M_S will be swept-up, and the following relation will hold:

$$\left(\frac{M_S}{1.5 \times 10^3 M_{\odot}} \right) \approx \left(\frac{n}{\text{cm}^{-3}} \right) \left(\frac{V}{10^2 \text{ km s}^{-1}} \right) \left(\frac{R}{3 \text{ pc}} \right)^2, \quad (6)$$

which, for a given M_S and R results in a simple relation between n and V .

A dense gaseous blob that is put in orbit within an ambient gaseous medium will experience ram pressure from the ambient medium. If this ram pressure is stronger than the gravitational restoring force provided by the potential well in which the dense gaseous blob resides, then the dense gas will be stripped away. The critical condition, when ram pressure equals the gravitational restoring force, can be determined via

$$\rho V^2 = \frac{GM_* M_g}{4\pi R^4}, \quad (7)$$

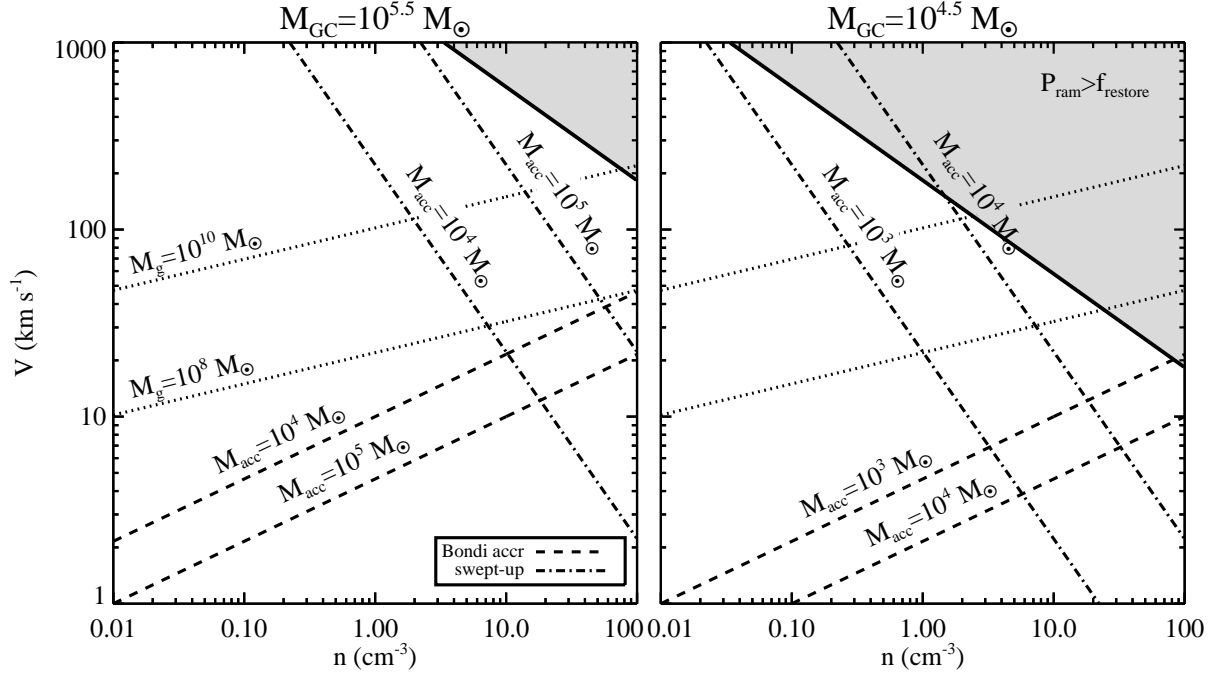


FIG. 2.— Comparison of the importance of ram pressure, Bondi accretion, and ambient ISM sweeping to the development of the gas reservoir within GCs (see Equations 4, 6, and 8). In this model, GCs begin with a gas reservoir with mass equal to 10% of the total mass (i.e., $f = 0.1$), have a half-mass radius of 3 pc, and move with velocity V through an ambient ISM with average density n . Left panel shows results for a GC with mass $10^{5.5} M_{\odot}$; right panel is for a GC of mass $10^{4.5} M_{\odot}$. Shaded zones are regions of parameter space where ram pressure is strong enough to remove the gas from a GC. Lines show the amount of material accreted by the GC after 10^8 yr by either Bondi accretion (dashed lines) or ambient ISM sweeping (dot-dashed lines). We also show in this figure the relation between V and n for the systems within which the GCs may be orbiting (dotted lines). This last relation is constructed by assuming gas-dominated self-gravitating systems (i.e., assuming $V^2 = GM_g/R$) with gas masses indicated in the figure.

where M_* is the total stellar mass of the GC, M_g and R are the mass and radius of gas within the GC, V is the orbital velocity of the GC, and ρ is the density of the ambient medium through which the GC moves. We will assume that $M_g = fM_*$ and take R to be the half-mass radius of the cluster. This yields the following expression for V :

$$V = 580 \left(\frac{n}{\text{cm}^{-3}} \right)^{-1/2} \left(\frac{f}{0.1} \right)^{1/2} \left(\frac{R}{3 \text{ pc}} \right)^{-2} \left(\frac{M}{10^5 M_{\odot}} \right) \text{ km s}^{-1}. \quad (8)$$

Notice the relatively strong dependence on radius. Observationally, the half-light radii and masses of MW GCs are only weakly correlated. It is possible that any primordial mass-radius relation has been erased by subsequent dynamical evolution. Nonetheless, in the absence of any convincing evidence to the contrary, we assume herein that *initial* GC masses and radii are uncorrelated. Unless stated otherwise, we will assume GC half-mass radii of 3 pc, which is the average half-mass radius of GCs in the MW as determined from the MW GC catalog of Harris (1996). GCs in other galaxies also have average half-light radii of 3 pc, independent of GC luminosity (e.g., Masters et al. 2010).

We emphasize that the relations derived above are only approximate. Variations by factors of several can occur depending on the detailed orbital properties, density profile of the GC and ambient ISM, and equation of state of the ambient ISM. These relations, and the discussion to follow, should be interpreted as a guide to the trends and order of magnitude effects to be expected.

The relative importance of these three processes is explored in Figures 2, 3, and 4. In Figure 2 we compare the importance of ram pressure, Bondi accretion, and ISM sweeping as a function of the velocity, V , and ambient ISM density, n . Recall that for Bondi accretion V can be interpreted as the sum in quadrature of the GC gas sound speed and the relative motion of the GC through the ambient ISM; for other mechanisms V should be interpreted simply as the relative velocity between the GC and the ambient medium. For the ram pressure calculations, we have assumed that the mass of the GC gas reservoir is 10% of the total GC mass (i.e., $f = 0.1$; this assumption is discussed at the end of the section). We have also assumed a GC radius of 3 pc, as per the discussion above. Results in Figure 2 are shown for GC masses of $10^{4.5} M_{\odot}$ and $10^{5.5} M_{\odot}$. The lower mass corresponds to the lowest MW GC mass in which multiple populations have been found (Carretta et al. 2010c). Also, in Figure 2 we show the relation between n and V for a gas-dominated, self-gravitating system, for two gas masses labeled in the figure. This relation is included as a rough guide to the properties of the host systems in which GCs may have been found at their formation epoch.

In Figure 3 we compare the same processes now as a function of V and GC mass, for a fixed number density of $n = 1 \text{ cm}^{-3}$ and $n = 100 \text{ cm}^{-3}$. Finally, in Figure 4 we show the ratio of total accreted mass to GC mass as a function of GC mass at four different environments.

There are several important conclusions to be drawn from these figures. First, for the *present* MW circular velocity ($V \approx 220 \text{ km s}^{-1}$) ram pressure will be sufficient to remove the

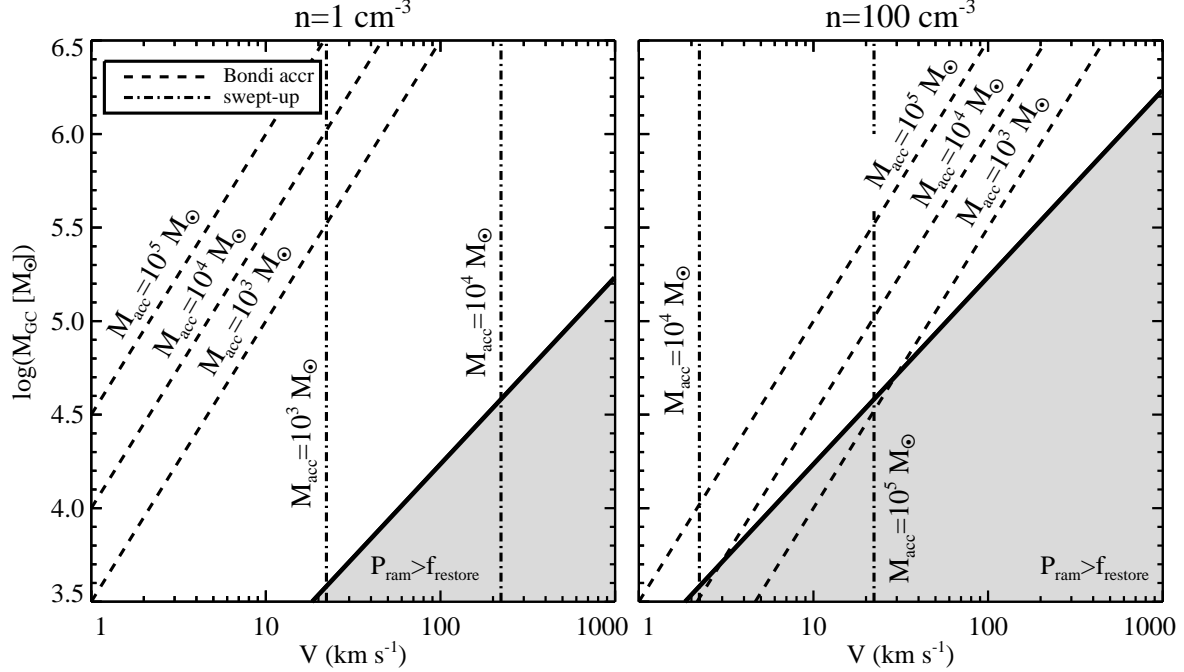


FIG. 3.— Comparison of the importance of ram pressure, Bondi accretion, and ambient ISM sweeping to the development of the gas reservoir within GCs. This figure is similar to Figure 2 except for a fixed ambient density of $n = 1 \text{ cm}^{-3}$ (left panel) and $n = 100 \text{ cm}^{-3}$ (right panel), and a range of GC masses, M_{GC} . Lines and shaded regions are as in Figure 2.

gas within the GC when the GC crosses the MW disk (where $n \sim 1 \text{ cm}^{-3}$) for GC masses $\lesssim 10^{4.5} M_{\odot}$. The circular velocity of the LMC is a factor of ≈ 3 lower than the MW (Kim et al. 1998), and so ram pressure will be able to remove the GC gas supply only in clusters a factor of ≈ 3 less massive⁵, or for $M < 10^4 M_{\odot}$. We therefore expect that *young* clusters forming with masses $\lesssim 10^{4.5} M_{\odot}$ in the MW should be truly coeval, while young clusters of comparable mass forming in the LMC may host multiple populations. The critical mass for MW GCs is considerably higher than typically assumed because of the high GC gas mass fraction assumed herein (10%), which is appropriate when considering the early development of GCs, when mass-loss rates are high. When one considers ram pressure effects in present day GCs, the gas mass fractions considered are typically less than 1%, and so ram pressure is much more effective (e.g., Frank & Gisler 1976; Gnedin et al. 2002).

Of course, the ancient MW GCs almost certainly formed in environments very different from the present day MW. While the present MW velocity is $V \approx 220 \text{ km s}^{-1}$, the velocity of the typical progenitor system in which the MW GCs formed was likely at least a factor of 10 lower. Thus, less massive ancient GCs may have also survived the effects of ram pressure (if we assume $V_{\text{proj}} \approx 20 \text{ km s}^{-1}$ and $n = 1 \text{ cm}^{-3}$ the critical mass becomes $10^{3.5} M_{\odot}$). It is because of this fact that we emphasized that the critical mass of $\sim 10^{4.5} M_{\odot}$ should be manifest in clusters forming in the MW and LMC at the *present epoch*. Without knowing in detail the properties of the progenitor systems in which MW GCs formed, one cannot discuss quantitatively

⁵ Notice that ram pressure scales as V^2 and the restoring force scales as $M_* M_g \propto M_*^2$. The critical GC mass therefore depends linearly on the velocity.

the effects of ram pressure on the early development of the ancient MW GCs.

As mentioned in §1, the only class of star clusters known *not* to contain multiple stellar populations are the open clusters in the MW (de Silva et al. 2009; Martell & Smith 2009). This population is much less massive than either the MW GCs or the LMC clusters, with typical masses of $\sim 10^3 M_{\odot}$. Based on Figure 3, it is not surprising that such low mass systems do not contain multiple populations because ram pressure would be effective at stripping gas within the GC for any plausible formation environment.

The right panel of Figure 3 shows the effects of ram pressure, Bondi accretion, and ISM sweeping when the ambient ISM density is $n = 100 \text{ cm}^{-3}$. These densities are very high compared to typical ISM environments in the local Universe, but may be common at the epoch of massive GC formation. For example, the bulge of the MW likely formed rapidly at $z \gtrsim 2$ (Zoccali et al. 2006; Ballero et al. 2007), has a stellar mass of $10^{10} M_{\odot}$ and a half-mass radius of $\approx 1 \text{ kpc}$ (Binney et al. 1997). If all the bulge stars were converted into gas, the gas density would be $n \sim 100 \text{ cm}^{-3}$ at the epoch of GC formation.

Finally, Figure 4 shows the total mass accreted within 10^8 yrs divided by the initial GC mass as a function of GC mass. Depending on the formation environment, clear trends are predicted for the total accreted mass as a function of initial GC mass. In particular, if the relative velocities were low and the ambient densities high (upper left panel) at the epoch of formation, one would expect an increasing fraction of accreted material as GC mass increases.

In this section we have assumed that the gas mass within the GC is only $f = 10\%$ of the GCs stellar mass. Of course, by

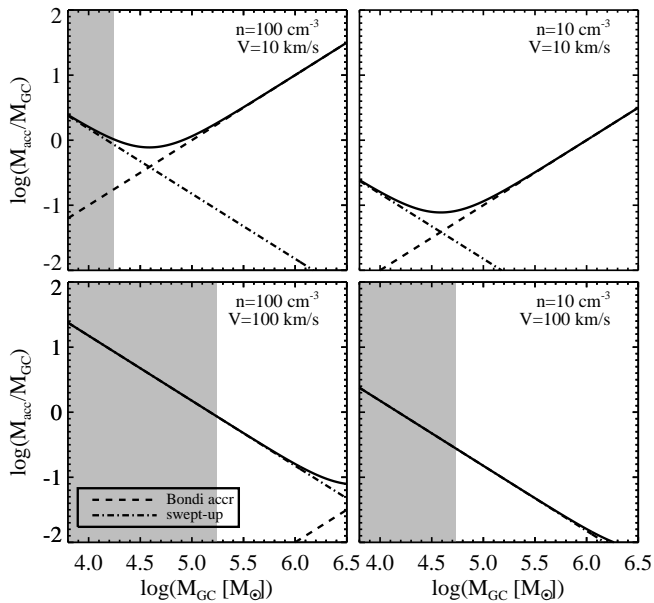


FIG. 4.— Comparison of the importance of ram pressure, Bondi accretion, and ambient ISM sweeping to the development of the gas reservoir within GCs. This figure is similar to Figures 2 and 3, except that here we show the fraction of mass accreted after 10^8 yr as a function of GC mass for a variety of environments. Shaded zones are regions of parameter space where ram pressure is sufficient to remove the GC gas supply. Solid lines show the combined effects of Bondi accretion and ISM sweeping.

the time the GC forms its second generation of stars, the gas mass fraction must be of order unity (or significantly greater than unity, depending on the star formation efficiency) in order to satisfy the observational constraint that the first and second generations are approximately equal in mass. Increasing f to unity results in a stronger restoring force and therefore a reduced ability of ram pressure to remove gas within the GC. The critical zone for ram pressure stripping is therefore time-dependent. A more thorough investigation that what has been presented herein will therefore require time-dependent model calculations. In particular, the initial development of a gaseous reservoir will depend on the detailed hydrodynamical interaction between the ambient medium and AGB outflows in the presence of the GC potential well.

4. CONSTRAINTS FROM INTERMEDIATE-AGE CLUSTERS IN THE LMC

In this section we present new evidence for an LMC cluster mass threshold below which LMC clusters appear to be truly coeval. This result is then discussed in the context of early GC evolutionary scenarios.

Multiple stellar populations have been detected in intermediate-age (~ 1 Gyr) and old LMC clusters (Mackey et al. 2008; Goudfrooij et al. 2009; Milone et al. 2009; Mucciarelli et al. 2009). The old clusters have masses of $\approx 10^{5.5} M_\odot$ (Mackey & Gilmore 2003); the masses of the intermediate-age clusters will be derived below. Intermediate-age clusters possess the property that age differences of $\sim 10^8$ yr are readily observable in the main sequence turn-off point because at these ages the turn-off point is a strong function of time.

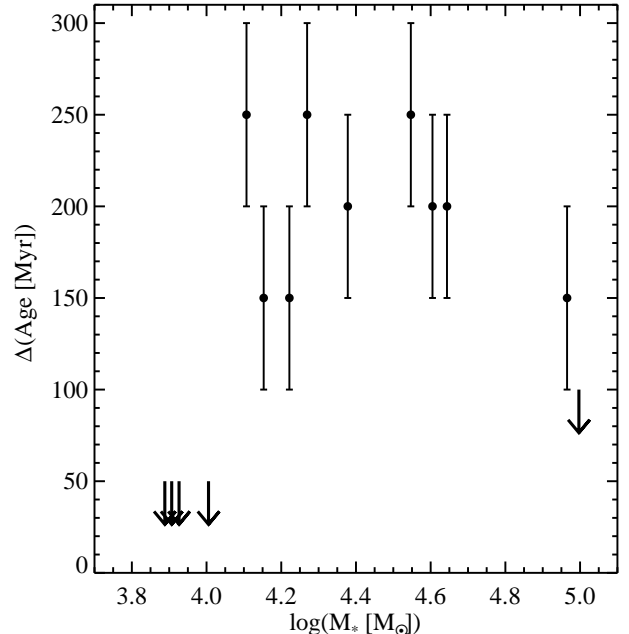


FIG. 5.— Internal age spread in intermediate-age LMC clusters as a function of cluster stellar mass. The age spreads are adopted from Milone et al. (2009) and are based on isochrone fits to *HST*-based CMDs. Stellar masses are derived herein. Upper limits indicate that the cluster is consistent with a single-age population. Notice that below $\log(M_*/M_\odot) \approx 4.0$ all LMC clusters are consistent with being coeval. The most massive cluster in this sample, NGC 1978, is also consistent with being coeval, although this cluster has a variety of peculiar properties; see the text for details. The lowest mass cluster has been shifted slightly in mass for clarity.

The identification of multiple populations in intermediate-age clusters is important for several reasons. First, the birth environment of such clusters cannot be dramatically different from the present day LMC, in contrast with the old clusters. This opens the possibility of making more direct links between the clusters and their environment than is possible with the old clusters. Second, as discussed in §2.1.1, these observations argue strongly against GC formation at the center of their own dark matter halos as a means to produce multiple populations.

Milone et al. (2009) has recently analyzed archival *HST* images of 16 intermediate-age clusters in the LMC. These authors derive not only average ages, metallicities, distances, and reddening values, but also the internal spread in age for each cluster in their sample. Only five of the clusters in their sample were consistent with being coeval. We are interested in knowing whether the internal age spreads measured by Milone et al. correlate with the mass of the cluster. We have therefore derived stellar masses for the clusters in Milone et al., in the following way. The average age of each cluster is converted into a V -band mass-to-light ratio, M/L_V , via the stellar population synthesis models of Conroy et al. (2009) as updated in Conroy & Gunn (2010). We assume $Z = 0.006$ for the young clusters in the LMC and a Kroupa (2001) IMF. We then adopt V -band magnitudes for the Milone et al. clusters from the data compilation of van den Bergh (1981) (there are fourteen clusters in common). These photometry are then corrected for extinction and converted to absolute luminosities via the $E(B-V)$ values and distance moduli listed in Milone

et al. Finally, stellar masses are estimated by combining the expected M/L_V and absolute magnitudes. The majority of the clusters have similar ages and so the estimated M/L_V s do not vary considerably across the sample. The following result therefore does not depend critically on the adopted modeling approach.

In Figure 5 we show the relation between the total stellar mass and internal age spread for the clusters in Milone et al. (2009). It is remarkable that all clusters with masses $\lesssim 10^4 M_\odot$ show no evidence for multiple populations. In the LMC, there appears to be a critical mass below which the formation of multiple populations is suppressed. This critical mass is fully consistent with our estimates of the effects of ram pressure effects in the LMC, where for $n = 1 \text{ cm}^{-3}$ and $V = 70 \text{ km s}^{-1}$ we find a critical mass of $M \approx 10^4 M_\odot$. Given the sensitivity to parameters such as the GC radius, a more quantitative comparison must await detailed observations of these clusters.

The most massive cluster in Figure 5, NGC 1978, also shows no evidence for multiple populations. It is worth noting that Milone et al. (2009) extract the CMD for their target clusters from the cluster core for all clusters except for NGC 1978 because of crowding. Since the second generation appears to be more spatially concentrated than the first (see §1), this may explain the observed lack of significant internal age spread in this cluster. This cluster has a number of peculiar properties, including a high ellipticity (Geisler & Hodge 1980), a lack of S stars, and odd carbon and oxygen ratios in its AGB stars (Lederer et al. 2009). Owing to all of these facts, we are reluctant to place much weight on the result that this massive cluster does not show obvious signs of internal age spreads.

Bastian & de Mink (2009) raise the possibility that the observed broadening of the CMD of intermediate-age LMC clusters is in fact due to stellar rotation, and not multiple populations. We believe this scenario to be implausible for several reasons. First, our results in Figure 5 strongly suggest that the width of the main sequence turn-off is related to the total cluster mass. This correlation is difficult to explain if the width was due to stellar rotation. Second, no such broadening is observed in the intermediate-age MW open clusters, including the Hyades, Pleiades, and Praesepe (e.g., Vandenberg & Bridges 1984; Griffin et al. 1988; Pinsonneault et al. 2004; An et al. 2007). These MW open clusters have masses of order $10^3 M_\odot$, and so in our scenario they should be truly coeval, as observed. The scenario of Bastian & de Mink can be reconciled with the open cluster data and low mass LMC data only by supposing an *ad hoc* correlation between stellar rotation rate and cluster mass, which seems implausible.

5. SUMMARY, OPEN ISSUES AND FUTURE DIRECTIONS

In this work we have presented a comprehensive model for the early (several 10^8 yr) evolution of massive star clusters. Our model considers the importance of type II and prompt type Ia SNe, accretion onto the GC from the ambient ISM, the ability of a GC to retain its internal gas supply in the face of ram pressure, and the effect of the Lyman-Werner photon flux density on the ability of the young GC gas to form molecules and, ultimately, stars.

This model definitively addresses two of the three major issues in early GC evolution identified in §2: how GCs can retain a gaseous reservoir in the face of ram pressure, and which stars are responsible for processing material to $T > 10^7 \text{ K}$. From consideration of the formation environments of both old

MW GCs and intermediate-age LMC clusters, we have shown that ram pressure stripping naturally explains the observed bifurcation between clusters that do and do not show evidence for multiple stellar populations. Based on several independent arguments, including the similar $\sim 10^8$ yr timescale of many physical mechanisms and the lack of internal spread in Fe and Ca in most clusters, we strongly favor massive AGB stars as the source of the processed material.

The final open issue is in understanding how a second generation can form with a current total mass comparable to the first generation, at least for old MW GCs where data are available. We have considered accretion from the ambient ISM as a viable mechanism to provide copious amounts of gas to the GC. However, our solution to this last issue currently has little direct empirical verification, and may in fact have trouble reproducing the observed correlations in abundance ratios, as discussed below. We now discuss a variety of testable implications of our proposed solution, and comment briefly on several open issues.

As a consequence of significant accretion from the ambient ISM, we expect several trends with GC mass (see e.g., Figure 4). For example, as the fraction of pristine gaseous material increases, we expect a shorter Na-O correlation, a greater abundance of Li and F, and in general we expect the stars with anomalous abundances to be less anomalous. The sign of the trend with mass depends on the dominant accretion process, which in turn depends on the formation environment. Bondi accretion scales as M^2 while the mass provided by AGB winds scales with M so the pristine fraction increases with mass. ISM sweeping scales as R^2 which is only weakly correlated with M at the present epoch, and so if this process is dominant we would expect the pristine fraction to decrease with mass.

Observations of young and intermediate-age clusters will allow identification of the relevant mechanism because the formation environment of young clusters is not so dissimilar from their present environment. The old GCs within dwarf spheroidals and dwarf irregulars may also shed light on this issue. The GCs within dwarf galaxies almost certainly formed where they are now observed since the stellar accretion/merger rate onto dwarfs is expected to be very low in a Λ CDM cosmology, and so the present day conditions of the host dwarf galaxies cannot be very different from the formation environment of the GCs.

Carretta (2006) and Carretta et al. (2010b) have investigated the extent of the Na-O correlation as a function of global parameters and have found evidence that the correlation is more extended in higher mass GCs, and for GCs with more extended orbits. This result is consistent with ISM sweeping being the dominant accretion process, but we caution that the data show large scatter, and the present GC mass is poorly correlated with its mass at formation due to orbit-dependent mass-loss effects. In general, we expect that the extent of the Na-O correlation should depend on the formation environment at fixed GC mass, since the formation environment determines the amount of accreted material. Another effect might be the mass-dependent ability of a GC to retain the winds from AGB stars. In any event, it is clear that such trends hold the promise of isolating which physical process dominates the accretion of pristine material onto GCs.

If accretion from the ambient ISM was important, then it is somewhat puzzling why the Fe and Ca abundances are so uniform between the first and second generations. The only plau-

sible explanation is that at early times, during the formation of the ancient MW GCs, the spread in Fe and Ca abundances within the MW progenitor system was quite small. A clear prediction of the accretion scenario is that the intermediate-age LMC clusters showing multiple populations should show a much larger internal spread in Fe, Ca, etc. abundances, on the order of the spread in abundances of these elements within the LMC as a whole.

The MW bulge GC Terzan 5 may provide additional insight. Ferraro et al. (2009) has convincingly shown that this GC has a split horizontal branch (HB) with the more luminous branch having a much higher Fe abundance ($[\text{Fe}/\text{H}] \sim +0.3$) than the less luminous branch ($[\text{Fe}/\text{H}] \sim -0.2$). D’Antona et al. (2010) argue that the split HB is consistent with an internal age spread of several 10^8 yr and enhanced He in the metal-enriched branch. Since this cluster is in the MW bulge and Fe-rich, it probably formed in the bulge. D’Antona et al. suggest that the second stellar generation may have acquired its high Fe abundance via accretion from the ambient, Fe-rich ISM. Self-enrichment is unlikely because the required Fe mass to produce the observed high Fe abundance would require so many type II SNe that the cluster would easily become unbound, unless Terzan 5 was significantly more massive in the past. Terzan 5 may therefore be an ideal cluster to look for further evidence for the importance of ambient ISM accretion in the formation of multiple stellar populations, e.g., by observing the Li and F abundances in this cluster. If the proposed scenario for Terzan 5 is generic then we might expect to find significantly separated Fe abundances within the other bulge metal-rich GCs as well.

In the present work we have not attempted to make specific predictions for the extent of correlations amongst various elemental abundances. Such predictions would provide a powerful constraint on the model. Qualitative considerations suggest that substantial accretion from the ISM may yield a very short Na-O anti-correlation, owing to the ISM having abundance ratios similar to the first generation stars. Unfortunately, uncertainties in the AGB yields greatly complicate any attempted comparison to observed abundances. A fruitful avenue for future work will consist of a detailed comparison between predicted and observed abundance correlations in light of the uncertain AGB yields (see D’Ercole et al. 2010, for an initial attempt in this direction).

The most massive GCs, including ω Cen, NGC 2808, M22, and M54, deserve special mention. Each of these clusters show multiple, *distinct* sequences in the CMD, and the former two are unique in that they display multiple main sequences. The CMD morphology of these clusters suggests very high He abundances in the second (and third) stellar generations. The discrete sequences and high He abundances argue against significant dilution from ambient ISM accretion. This can be accommodated in our model if ISM sweeping is the dominant accretion mechanism because this mechanism becomes increasingly less important at high GC masses (see the bottom panels of Figure 4). Although we are then left with the original problem of explaining how so many second generation stars could form from the mass lost by the first generation. We speculate that perhaps the most massive GCs formed at the centers of their own dark matter halos, and contained

even more stars in their past. The precursors of these systems could be nuclear star clusters, which are common in low-mass galaxies. Regardless of these details, we stress caution when attempting to incorporate the massive GCs into any framework for the early evolution of GCs since many of their observational characteristics differ qualitatively from the lower mass GCs.

An exciting direction for future observational work is characterizing the incidence of multiple populations within the numerous young and intermediate-age clusters in M31. These clusters span a range in mass from $10^3 M_\odot$ to $10^5 M_\odot$ (Caldwell et al. 2009). Based on ram pressure arguments, we expect the higher mass clusters to show evidence for multiple populations, but not the lower mass clusters. Assuming $n = 1 \text{ cm}^{-3}$ and $V = 250 \text{ km s}^{-1}$ for disk of M31 (Widrow et al. 2003), we predict that the critical mass will be $\approx 10^{4.5} M_\odot$. However, as stressed in previous sections, the relevant velocity is the relative velocity between the ambient ISM and the GC. Since many of the young M31 GCs are orbiting within the disk of M31, their relative velocity will be considerably less than the circular velocity, and so the critical mass may be considerably lower. Confrontation of our model predictions with the properties of the M31 GCs must take these details into account.

Since these M31 clusters have not experienced significant dynamical evolution, we may expect stronger correlations between the extent of any abundance anomalies and cluster mass. For the youngest clusters, with ages of several 10^8 yr, we might even hope to *directly observe* the formation of the second generation. Such an observation would provide definitive proof that GCs need not form within dark matter halos to produce multiple stellar generations, and would also demonstrate that AGB stars are the polluters, since the AGB polluter scenario is expected to produce a second generation on a timescale of several 10^8 yr.

In the past several years it has become clear that star clusters, once thought to be simple systems, in fact show an internal complexity that increases with increasing mass. Observations indicate that the lowest mass systems, i.e., the open clusters, appear to be truly coeval and mono-metallic. At higher masses one observes age spreads of several 10^8 yr and internal variation in the light elements. At still higher masses ($\gtrsim 10^6 M_\odot$) it appears that the cluster potential well is deep enough to retain SNe ejecta and hence self-enrich, perhaps because these massive clusters form at the center of their own dark matter halos. This last phenomenon is observed not only in the most massive MW GCs, but also appears to be present in the most massive GCs within other galaxies as well (Strader & Smith 2008; Bailin & Harris 2009). At the very least, it is now abundantly clear that star clusters are not simple systems.

We acknowledge fruitful conversations with Bruce Draine, and thank Alvio Renzini for comments on an earlier draft. The referee is thanked for comments that improved the quality of the manuscript. This work made extensive use of the NASA Astrophysics Data System and of the *astro-ph* preprint archive at arXiv.org.

REFERENCES

- An, D., Terndrup, D. M., Pinsonneault, M. H., Paulson, D. B., Hanson, R. B., & Stauffer, J. R. 2007, *ApJ*, 655, 233
 Bailin, J. & Harris, W. E. 2009, *ApJ*, 695, 1082
 Ballero, S. K., Matteucci, F., Origlia, L., & Rich, R. M. 2007, *A&A*, 467, 123
 Bastian, N. & de Mink, S. E. 2009, *MNRAS*, 398, L11

- Baumgardt, H., Côté, P., Hilker, M., Rejkuba, M., Mieske, S., Djorgovski, S. G., & Stetson, P. 2009, *MNRAS*, 396, 2051
- Baumgardt, H., Kroupa, P., & Parmentier, G. 2008, *MNRAS*, 384, 1231
- Bekki, K., Campbell, S. W., Lattanzio, J. C., & Norris, J. E. 2007, *MNRAS*, 377, 335
- Bekki, K. & Norris, J. E. 2006, *ApJ*, 637, L109
- Binney, J., Gerhard, O., & Spergel, D. 1997, *MNRAS*, 288, 365
- Böker, T. 2008, *ApJ*, 672, L111
- Böker, T., Sarzi, M., McLaughlin, D. E., van der Marel, R. P., Rix, H., Ho, L. C., & Shields, J. C. 2004, *AJ*, 127, 105
- Bondi, H. 1952, *MNRAS*, 112, 195
- Brandt, T. D., Tojeiro, R., Aubourg, É., Heavens, A., Jimenez, R., & Strauss, M. A. 2010, *AJ*, 140, 804
- Bromm, V. & Clarke, C. J. 2002, *ApJ*, 566, L1
- Caldwell, N., Harding, P., Morrison, H., Rose, J. A., Schiavon, R., & Kriessler, J. 2009, *AJ*, 137, 94
- Carretta, E. 2006, *AJ*, 131, 1766
- Carretta, E., Bragaglia, A., Gratton, R., D'Orazi, V., & Lucatello, S. 2009a, *A&A*, 508, 695
- Carretta, E., Bragaglia, A., Gratton, R., Lucatello, S., Bellazzini, M., & D'Orazi, V. 2010a, *ApJ*, 712, L21
- Carretta, E., Bragaglia, A., Gratton, R. G., Recio-Blanco, A., Lucatello, S., D'Orazi, V., & Cassisi, S. 2010b, *A&A*, 516, A55
- Carretta, E. et al. 2009b, *A&A*, 505, 117
- . 2010c, *ApJ*, 714, L7
- Cohen, J. G. 1978, *ApJ*, 223, 487
- Conroy, C. & Gunn, J. E. 2010, *ApJ*, 712, 833
- Conroy, C., Gunn, J. E., & White, M. 2009, *ApJ*, 699, 486
- Cottrell, P. L. & Da Costa, G. S. 1981, *ApJ*, 245, L79
- D'Antona, F. & Caloi, V. 2004, *ApJ*, 611, 871
- D'Antona, F., Caloi, V., Montalbán, J., Ventura, P., & Gratton, R. 2002, *A&A*, 395, 69
- D'Antona, F., Ventura, P., Caloi, V., D'Ercole, A., Vesperini, E., Carini, R., & Di Criscienzo, M. 2010, *ApJ*, 715, L63
- de Mink, S. E., Pols, O. R., Langer, N., & Izzard, R. G. 2009, *A&A*, 507, L1
- de Silva, G. M., Gibson, B. K., Lattanzio, J., & Asplund, M. 2009, *A&A*, 500, L25
- Decressin, T., Meynet, G., Charbonnel, C., Prantzos, N., & Ekström, S. 2007, *A&A*, 464, 1029
- D'Ercole, A., D'Antona, F., Ventura, P., Vesperini, E., & McMillan, S. L. W. 2010, *MNRAS*, 407, 854
- D'Ercole, A., Vesperini, E., D'Antona, F., McMillan, S. L. W., & Recchi, S. 2008, *MNRAS*, 391, 825
- Dopita, M. A. & Smith, G. H. 1986, *ApJ*, 304, 283
- Fabian, A. C., Pringle, J. E., & Rees, M. J. 1975, *MNRAS*, 172, 15P
- Ferraro, F. R. et al. 2009, *Nature*, 462, 483
- Frank, J. & Gisler, G. 1976, *MNRAS*, 176, 533
- Freeman, K. C. 1993, in *Astronomical Society of the Pacific Conference Series*, Vol. 48, *The Globular Cluster-Galaxy Connection*, ed. G. H. Smith & J. P. Brodie, 608
- Freeman, K. C. & Norris, J. 1981, *ARA&A*, 19, 319
- Geisler, D. & Hodge, P. 1980, *ApJ*, 242, 66
- Gnedin, O. Y., Zhao, H., Pringle, J. E., Fall, S. M., Livio, M., & Meylan, G. 2002, *ApJ*, 568, L23
- Goerdt, T., Moore, B., Read, J. I., Stadel, J., & Zemp, M. 2006, *MNRAS*, 368, 1073
- Goudfrooij, P., Puzia, T. H., Kozhurina-Platais, V., & Chandar, R. 2009, *AJ*, 137, 4988
- Gratton, R., Sneden, C., & Carretta, E. 2004, *ARA&A*, 42, 385
- Gratton, R. G., Carretta, E., Bragaglia, A., Lucatello, S., & D'Orazi, V. 2010, *A&A*, 517, A81
- Gratton, R. G. et al. 2001, *A&A*, 369, 87
- Griffin, R. F., Griffin, R. E. M., Gunn, J. E., & Zimmerman, B. A. 1988, *AJ*, 96, 172
- Grillmair, C. J., Freeman, K. C., Irwin, M., & Quinn, P. J. 1995, *AJ*, 109, 2553
- Hansen, B. M. S. & Phinney, E. S. 1997, *MNRAS*, 291, 569
- Harris, W. E. 1996, *AJ*, 112, 1487
- Ivans, I. I., Sneden, C., Kraft, R. P., Suntzeff, N. B., Smith, V. V., Langer, G. E., & Fulbright, J. P. 1999, *AJ*, 118, 1273
- Jura, M. 1975, *ApJ*, 197, 575
- Karakas, A. & Lattanzio, J. C. 2007, *Publications of the Astronomical Society of Australia*, 24, 103
- Kim, S., Staveley-Smith, L., Dopita, M. A., Freeman, K. C., Sault, R. J., Kesteven, M. J., & McConnell, D. 1998, *ApJ*, 503, 674
- Kraft, R. P. 1979, *ARA&A*, 17, 309
- Kraft, R. P., Sneden, C., Langer, G. E., & Shetrone, M. D. 1993, *AJ*, 106, 1490
- Kroupa, P. 2001, *MNRAS*, 322, 231
- Lederer, M. T., Lebzelter, T., Cristallo, S., Straniero, O., Hinkle, K. H., & Aringer, B. 2009, *A&A*, 502, 913
- Letarte, B., Hill, V., Jablonka, P., Tolstoy, E., François, P., & Meylan, G. 2006, *A&A*, 453, 547
- Lotz, J. M., Miller, B. W., & Ferguson, H. C. 2004, *ApJ*, 613, 262
- Mackey, A. D., Broby Nielsen, P., Ferguson, A. M. N., & Richardson, J. C. 2008, *ApJ*, 681, L17
- Mackey, A. D. & Gilmore, G. F. 2003, *MNRAS*, 338, 85
- Mackey, A. D. et al. 2010, *MNRAS*, 401, 533
- Maoz, D., Sharon, K., & Gal-Yam, A. 2010, *ApJ*, 722, 1879
- Marino, A. F., Milone, A. P., Piotto, G., Villanova, S., Bedin, L. R., Bellini, A., & Renzini, A. 2009, *A&A*, 505, 1099
- Marino, A. F., Villanova, S., Piotto, G., Milone, A. P., Momany, Y., Bedin, L. R., & Medling, A. M. 2008, *A&A*, 490, 625
- Martell, S. L. & Smith, G. H. 2009, *PASP*, 121, 577
- Mashchenko, S. & Sills, A. 2005, *ApJ*, 619, 258
- Masters, K. L. et al. 2010, *ApJ*, 715, 1419
- Milone, A. P., Bedin, L. R., Piotto, G., & Anderson, J. 2009, *A&A*, 497, 755
- Milone, A. P. et al. 2010, *ApJ*, 709, 1183
- Moore, B. 1996, *ApJ*, 461, L13
- Mucciarelli, A., Origlia, L., Ferraro, F. R., & Pancino, E. 2009, *ApJ*, 695, L134
- Odenkirchen, M. et al. 2003, *AJ*, 126, 2385
- Pasquini, L., Bonifacio, P., Molaro, P., Francois, P., Spite, F., Gratton, R. G., Carretta, E., & Wolff, B. 2005, *A&A*, 441, 549
- Peebles, P. J. E. 1984, *ApJ*, 277, 470
- Peterson, R. C. 1980, *ApJ*, 237, L87
- Pflamm-Altenburg, J. & Kroupa, P. 2009, *MNRAS*, 397, 488
- Pinsonneault, M. H., Terndrup, D. M., Hanson, R. B., & Stauffer, J. R. 2004, *ApJ*, 600, 946
- Piotto, G. 2009, in *IAU Symposium*, Vol. 258, *IAU Symposium*, ed. E. E. Mamajek, D. R. Soderblom, & R. F. G. Wyse, 233–244
- Prantzos, N. & Charbonnel, C. 2006, *A&A*, 458, 135
- Prantzos, N., Charbonnel, C., & Iliadis, C. 2007, *A&A*, 470, 179
- Renzini, A. 2008, *MNRAS*, 391, 354
- Scannapieco, E. & Bildsten, L. 2005, *ApJ*, 629, L85
- Sills, A. & Glebbeek, E. 2010, *MNRAS*, 407, 277
- Smith, G. H. 1987, *PASP*, 99, 67
- Smith, G. H. & Norris, J. 1982a, *ApJ*, 254, 594
- . 1982b, *ApJ*, 254, 149
- . 1983, *ApJ*, 264, 215
- Smith, V. V., Cunha, K., Ivans, I. I., Lattanzio, J. C., Campbell, S., & Hinkle, K. H. 2005, *ApJ*, 633, 392
- Sollima, A., Ferraro, F. R., Bellazzini, M., Origlia, L., Straniero, O., & Pancino, E. 2007, *ApJ*, 654, 915
- Strader, J. & Smith, G. H. 2008, *AJ*, 136, 1828
- Tayler, R. J. & Wood, P. R. 1975, *MNRAS*, 171, 467
- Tumlinson, J. et al. 2002, *ApJ*, 566, 857
- van den Bergh, S. 1981, *A&AS*, 46, 79
- van der Marel, R. P. 2004, in *Coevolution of Black Holes and Galaxies*, ed. L. C. Ho, 37
- Vandenberg, D. A. & Bridges, T. J. 1984, *ApJ*, 278, 679
- Ventura, P. & D'Antona, F. 2008a, *MNRAS*, 385, 2034
- . 2008b, *A&A*, 479, 805
- . 2009, *A&A*, 499, 835
- . 2010, *MNRAS*, 402, L72
- Ventura, P., D'Antona, F., Mazzitelli, I., & Gratton, R. 2001, *ApJ*, 550, L65
- Verbunt, F. & Hut, P. 1987, in *IAU Symposium*, Vol. 125, *The Origin and Evolution of Neutron Stars*, ed. D. J. Helfand & J.-H. Huang, 187
- Walcher, C. J. et al. 2005, *ApJ*, 618, 237
- . 2006, *ApJ*, 649, 692
- Widrow, L. M., Perrett, K. M., & Suyu, S. H. 2003, *ApJ*, 588, 311
- Wolfire, M. G., Tielens, A. G. G. M., Hollenbach, D., & Kaufman, M. J. 2008, *ApJ*, 680, 384
- Yong, D., Grundahl, F., Johnson, J. A., & Asplund, M. 2008, *ApJ*, 684, 1159
- Zoccali, M., Pancino, E., Catelan, M., Hempel, M., Rejkuba, M., & Carrera, R. 2009, *ApJ*, 697, L22
- Zoccali, M. et al. 2006, *A&A*, 457, L1